Quantum oscillations of rectified dc voltage as a function of magnetic field in an "almost" symmetric superconducting ring

V. I. Kuznetsov,* A. A. Firsov, and S. V. Dubonos
Institute of Microelectronics Technology and High Purity Materials, Russian Academy of Sciences, 142432 Chernogolovka, Moscow Region, Russia

(Dated: February 2, 2008)

Periodic quantum oscillations of a rectified dc voltage $V_{dc}(B)$ vs the perpendicular magnetic field B were measured near the critical temperature T_c in a single superconducting aluminum almost symmetric ring (without specially created circular asymmetry) biased by alternating current with a zero dc component. With varying bias current and temperature, these $V_{dc}(B)$ oscillations behave like the $V_{dc}(B)$ oscillations observed in a circular-asymmetric ring but are of smaller amplitude. The Fourier spectra of the $V_{dc}(B)$ functions exhibit a fundamental frequency, corresponding to the ring area, and its higher harmonics. Unexpectedly, satellite frequencies depending on the structure geometry and external parameters were found next to the fundamental frequency and around its higher harmonics.

PACS numbers: 74.40.+k, 74.78.Na, 73.40.Ei, 03.67.Lx, 85.25.-j

The effect of ac voltage rectification in a superconducting thin-film asymmetric ring with a specially created circular asymmetry was recently reported [1]. Unlike previously proposed rectifiers which contained superconducting loops with tunnel or point contacts [2], the asymmetric structure proposed in [1] is the simplest and most efficient ac voltage rectifier with a high magnetic-field-dependent output signal.

Time-averaged rectified dc voltage $V_{dc}(B)$ was observed in a circular-asymmetric ring [1] threaded by a magnetic flux and biased by a low-frequency sinusoidal current (without a dc component) with an amplitude close to the critical one at temperatures slightly below T_c. $V_{dc}(B)$ is an odd function with respect to B and is periodically dependent on B with the period $\Delta B = \Phi_0/S$, where Φ_0 is the superconducting magnetic flux quantum and S is the effective ring area [1]. The experimental results in [1] provide indirect arguments for the $V_{dc}(B)$ voltage in a single asymmetric ring is directly proportional to the ring circulating current I_R. It can then be supposed that $V_{dc}(B)$ functions measured at various parameters can be used instead of I_R functions to describe the quantum state of an asymmetric structure.

The interest to asymmetric rings [1] was also due to that such but extremely thin-wall rings biased by a microwave current at $T < 0.5T_c$ could be used in a novel superconducting flux qubit with quantum phase-slip centers [3].

In this work, we report an experimental investigation of ac voltage rectification in a ring where circular asymmetry was not specially created. The rings studied were slightly geometrically distorted, the distortion arose during structure fabrication and was about 10% of the ring major wire width. In spite of a weak circular asymmetry of the rings, the observed rectification effect was fairly large.

The sample studied was a thin-film aluminum structure d = 50 nm thick. It was fabricated by thermal Al deposition onto a silicon substrate, using the lift-off process of electron beam lithography with proximity effect correction. An atomic-force microscopy (AFM) image of the structure in an 8.26×8.26 μm^2 window is shown in Fig. 1. The ring with a 10% wire widening in the upper ring part is in the center of the structure. The width of all narrow wires, except the widened part, is $w_n = 0.43 \pm 0.02$ μm, the width of the widened part is $w_w = 0.48 \pm 0.02$ μm (Fig. 1). The areas of the inner and outer ring contours are S_{in} = 8.3 μm^2 and S_{en} = 13.2 μm^2, respectively. The averaged geometrical area of the ring is, then, S_g = 10.75 μm^2. The structure resistance in the normal state at T = 4.2 K is $R_{4.2}$ = 26 Ω, the ratio of the room to helium temperature resistance is $R_{300}/R_{4.2}$ = 2, the electron effective mean free path is l = 10 nm, T_c = 1.360 K, and the superconducting coherence length is $\xi(0)$ = 110 nm.

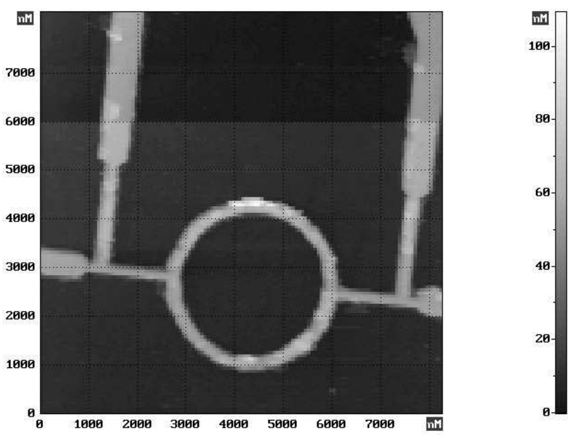

FIG. 1: AFM image of the structure in a 8260×8260 nm^2 window. The outer diameter of the ring is 4.1 μm.

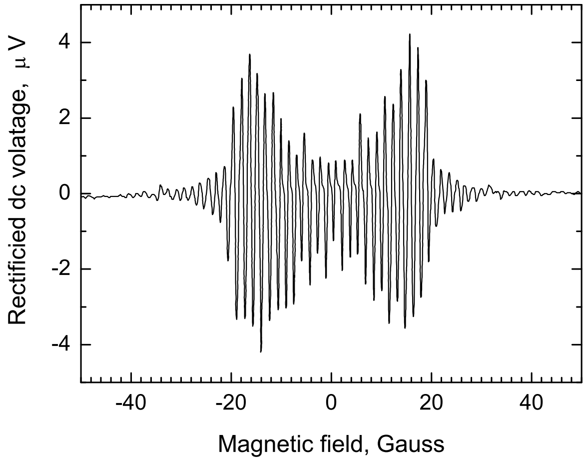

FIG. 2: $V_{dc}(B)$ in the structure at a sinusoidal current of $\nu = 1.23$ kHz with $I_\nu = 2.4$ μA at $T = 1.335$ K.

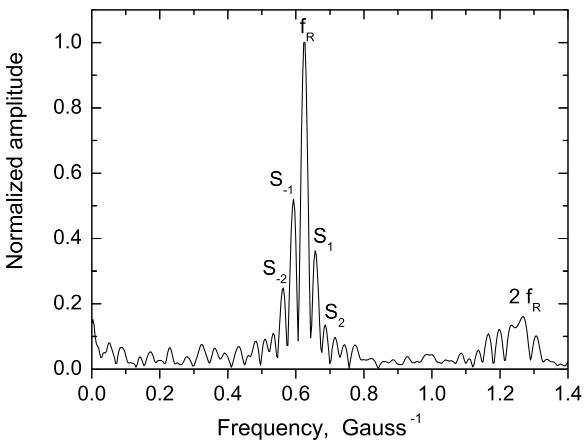

FIG. 3: Fourier spectrum of the function $V_{dc}(B)$. The symbols S_{-2}, S_{-1}, S_1, and S_2 refer to satellite frequencies.

$V_{dc}(B)$ oscillations were experimentally studied in structures similar to that in Fig. 1 at various amplitudes of bias bias alternating current (without a dc component) close to the critical amplitude at temperatures slightly lower than T_c. The magnetic field perpendicular to the structure surface was slowly varied during $V_{dc}(B)$ measurements. The $V_{dc}(B)$ curve measured in the structure of Fig. 1 biased by a sinusoidal current of $\nu = 1.23$ kHz with the amplitude $I_\nu = 2.4$ μA at $T = 1.335$ K is shown in Fig. 2. The amplitude of the $V_{dc}(B)$ oscillations behaves non-monotonically and is maximum at 17 Gauss. In fields higher than 40 Gauss, these oscillations become virtually imperceptible. As I_ν increases, the highest maximum of the $V_{dc}(B)$ oscillations shifts towards lower fields, because the amplitude of the oscillations depends both on bias current and magnetic field.

For a detailed analysis, the fast Fourier transformation (FFT) of the $V_{dc}(B)$ curve is calculated. Fig. 3 shows the FFT spectrum obtained using 2^{12} uniformly distributed points in the range from -150 to $+150$ Gauss. The fundamental frequency of the ring f_R is the inverse value of the fundamental oscillation period, i.e. $f_R = 1/\Delta B_R = S/\Phi_0$. The fundamental frequency value expected from the ring averaged geometrical area S_g is $f_g = 0.52$ Gauss^{-1}. Indeed, the FFT spectrum exhibits a peak at $f_R = 0.62$ Gauss^{-1} close to the geometric value f_g (Fig. 3).

Apart from the fundamental frequency f_R, the spectrum contains its higher harmonics $f_{Rm} = mf_R$, where $m = 2, 3, 4, \ldots$. Moreover, additional satellite peaks around the fundamental frequency and higher harmonics are observed at frequencies $f_{Sn} = f_R + n\Delta f$ and $f^m_{Sn} = mf_R + n\Delta f$ ($n = \ldots, -3, -2, -1, 1, 2, 3, \ldots$), respectively. For this curve (Fig. 2), the low-frequency value is $\Delta f = 0.03$ Gauss^{-1} and corresponds to the magnetic field $B_c = 33$ Gauss. It is seen that Δf determines the low-frequency background, with higher-frequency quantum oscillations superimposed on it. As external parameters and the sample geometry change, B_c behaves like a field suppressing the superconducting order parameter in the ring wires but is of slightly smaller value. So, satellite frequencies arise due to a combined effect of bias alternating and circulating currents and are dependent on the magnetic depairing factor.

Thus, rings of geometrical inhomogenecity up to 5% of the major wire width were fabricated. Some structures had the narrowings (widenings) by 10% with respect to the wire width. In these structures, the effect of ac voltage rectification was well observable. Since the magnetic-field-dependent electron quantum transport in almost symmetric superconducting loops is usually studied, using a modulation of the measuring dc current by a weak bias ac current, the side effect of ac voltage rectification, which can arise in the structures but was previously disregarded, should be taken into consideration.

We are grateful to V. L. Gurtovoi, A. V. Nikulov, and V. A. Tulin for helpful discussions. The work was supported by the program "Organization of Calculations Based on New Physical Principles" (Department of Information Technologies and Computer Systems, RAS) and the program "Quantum Macrophysics" (Presidium of RAS).

* Electronic address: kvi@ipmt-hpm.ac.ru

[1] S. V. Dubonos et al., JETP Lett. **77**, 371 (2003), cond-mat/0303538.
[2] I. Zapata et al., Phys. Rev. Lett. **77**, 2292 (1996).
[3] J. E. Mooij and C. J. P. M. Harmans, New Journal of Physics **7**, 219 (2005).